Plasma Arc Extinction Events - Insights from High-Speed Photography and Modelling

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Abstract: The operational problem of plasma arc extinction in direct-current (DC) arc furnaces used for metallurgical processing is examined using high-speed photography, electrical measurement, and modelling methods. Certain repeatable phenomena were observed in the behaviour of the arc in the short period of time before an extinction event, and some qualitative agreement between computational models and high-speed measurements was obtained. Results from this work were applied to a simple circuit model of a DC power supply, and lead to the conjecture that phenomena which cause a momentary increase in the electrical resistance of the arc column can result in arc extinction events when operating at extreme arc lengths.

Key words: high-speed, imaging, modelling, plasma, arc, furnace

1. Introduction

Direct-current plasma arc furnaces are used extensively in melting and smelting operations for the production of a wide range of industrially-significant materials such as steel, ferro-alloys, titanium dioxide, and platinum group metals [Jones et al. (2006)]. The plasma arc forms the primary heating and stirring element in this type of furnace; the arc is a fast-moving jet of ionised gas at high temperature, and completes the electric circuit between the furnace's single graphite cathode and the bath of molten process material which serves as the anode [Bowman (1994)].

Strong coupling between momentum, temperature, and electromagnetic fields sustain the arc's existence. Due to the very large driving forces and high velocities involved, the arc is an extremely dynamic phenomenon. Time scales typical of arc motion are of the order of milliseconds or less, and the arc column can form complex three-dimensional structures in space. The study of arcs therefore lends itself naturally to high-speed photography and computational modelling approaches [Reynolds et al. (2010)].

Of particular interest to the designers and operators of DC arc furnace plants is the behaviour of the plasma arc before and during unintentional loss of arc, or arc extinction - such events can result in significant furnace downtime and loss of production. Failure of the arc may occur for a number of reasons including gas or vapour evolution from the molten bath, damage to the graphite cathode, or excessive cooling of the plasma when operating with long arcs under high-voltage, low-current conditions. The latter case is the focus of the present study.

High-speed measurement equipment (both photographic and electrical) was applied to the examination of arcs close to the point of extinction. Information gained from the measurements were then used in a three-dimensional computational plasma arc model to confirm the qualitative understanding of the phenomena occurring. Finally, a simple circuit model of the furnace power supply and arc was used to provide a possible explanation

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for arc extinction when certain phenomena occur.

2. Equipment and experimental approach

A pilot-plant scale 3.2MVA IGBT [Ladoux et al. (2005)] furnace rectifier was used to generate arcs in air at ambient temperature and pressure. The arcs were operated at currents in the 1-3 kA range between a 200mm diameter graphite cathode mounted vertically in a hydraulic hoist, and a flat graphite block anode at ground level.

For each test, the arc was forced to extinguish by raising the cathode until the arc was lost, which typically occurred at between 30cm and 40cm arc length (measured between tip of cathode and surface of anode). Behaviour immediately before and during the extinction event was captured using a synchronously-triggered high-speed camera and electrical measurement system.

The high-speed camera used was an Olympus iSpeed 3 4GB colour unit. Unless otherwise noted, the camera was set to record at 5000 frames per second at 2μs shutter speed and 800x600 pixel resolution, and was positioned approximately 4m from the centerline of the arc region. A Tokina 80-200mm lens set at 200mm and f/22 aperture was used. Additional lighting was not required as the arc emits a large amount of visible light.

The electrical measurement system is a prototype under active development, and is based on the Mintek Arcmon [Barker et al. (2007)] technology platform. For these tests, measurements of voltage and current were recorded at 30kHz sample rate. Voltage was measured via direct cable connection to the anode and cathode, and current was measured via a 4-20mA signal sent from the rectifier's internal power control electronics.

A custom-built trigger unit was used to send a standard 5V TTL trigger to both the camera and the electrical measurement system simultaneously, resulting in synchronised image and electrical data. The entire system was manually triggered when the arc behaviour of interest was observed.

3. Results and discussion

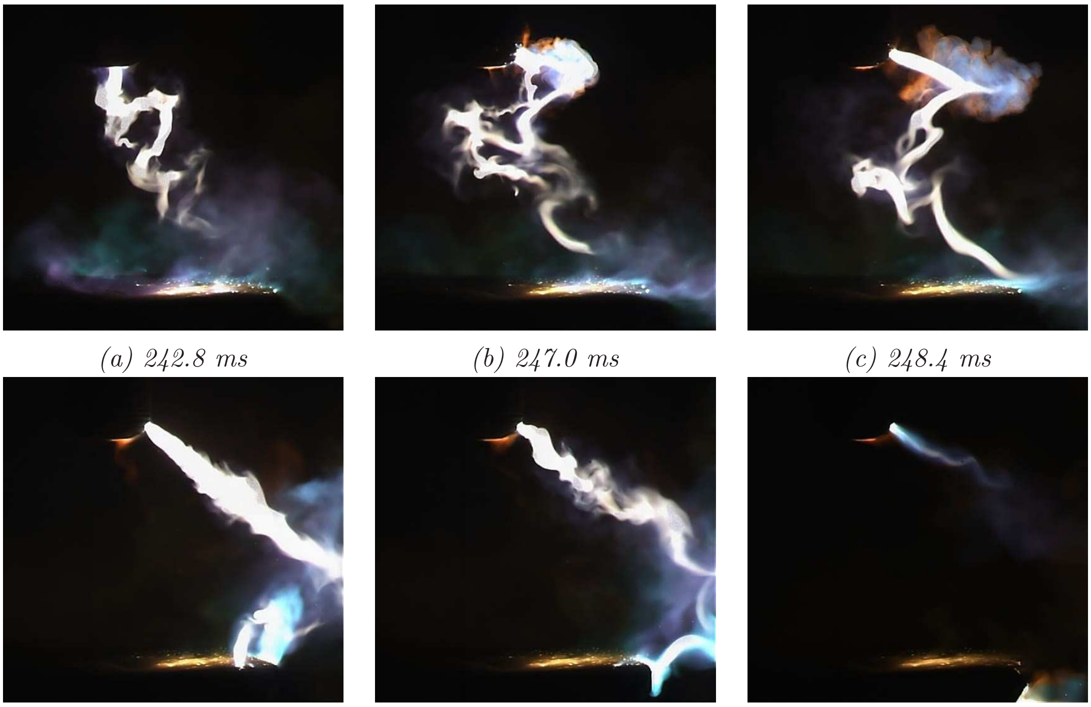
20 separate arc extinction tests were carried out over the period from September 2011 to May 2012, with additional tests to examine details of transitions in arc behaviour. The majority of the tests focused on behaviour at higher current levels (3kA).

High-speed video footage of each test was carefully examined frame by frame in order to identify any repeatable phenomena in the short period of time ($<$ 1s) prior to the extinction of the arc. It was observed that a particular sequence of three events frequently precipitated the loss of the arc:

- Formation of a gas/plasma fireball at the surface of the cathode electrode
- Establishment of a temporary pseudo-steady arc jet as the fireball disperses
- Collapse of the pseudo-steady state into normal chaotic arc motion

Arc extinction was most often correlated with either the first step (formation of the fireball) or the last step (transition to chaotic motion). Typically, the fireball formation and dispersal is a fast event, taking 5-10ms. The pseudo-steady state however is more variable in duration and can persist for up to 200ms. The break-down of the pseudo-steady state and resumption of chaotic arc motion prior to arc extinction is again a rapid phenomenon, taking less than 30ms.

A full extinction event sequence at 3kA is shown in Figure 1. In Figure 1(a), the arc is operating in a normal highly chaotic dynamic state. Figures 1(b) and (c) show the formation of a fireball of gas and plasma originating at the surface of the cathode near to the root of the arc jet and being pushed out into the bulk plasma (upper right of image). In Figure 1(d), the pseudo-steady state with a strong, constant arc jet directed away from the cathode is established. Figure 1(e) shows the deterioration of the steady behaviour and the onset of transient dynamics in the arc jet. Finally, in Figure 1(f) the arc is extinguished.

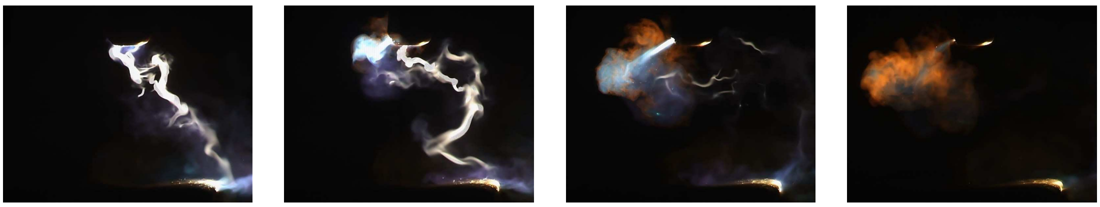


(a) 242.8 ms *(b) 247.0 ms* *(c) 248.4 ms*

(d) 262.2 ms *(e) 266.4 ms* *(f) 293.2 ms*

Figure 1. Sequence of frames from arc extinction test at 3kA, showing multiple transition events at different times

In Figure 2, a different test sequence is shown in which the extinction event occurs immediately after the fireball formation. The current setpoint is again 3kA for this test. Figure 2(a) shows the arc operating in the normal chaotic transient regime, followed by emission of a gas/plasma fireball from the cathode surface at upper left in Figures 2(b) and (c). In this case the arc immediately exinguishes before the pseudo-steady state can fully develop, as shown in Figure 2(d).



(a) 220.6 ms *(b) 226.2 ms* *(c) 232.0 ms* *(d) 238.2 ms*

Figure 2. Sequence of frames from arc extinction test at 3kA, showing fireball event at different times

Settings and qualitative observations from all arc extinction tests conducted are shown in Table 1. The duration of the entire extinction sequence is measured from the first deviation from normal arc behaviour to the point at which the arc is visibly extinguised (voltage goes to open-circuit value).

Table 1. List of test details and observed results from high-speed video footage

Test ID	*Current*	*Reason for arc extinction*	*Duration of extinction-event behaviour*
a-ARC08	1 kA	None observed	-
a-ARC09	1 kA	Pseudo-steady to chaotic transition	283.2 ms
a-ARC10	1 kA	Pseudo-steady to chaotic transition	237.0 ms
a-ARC11	2 kA	Pseudo-steady to chaotic transition	124.4 ms
a-ARC12	2 kA	Cathode fireball	24.8 ms
a-ARC13	2 kA	Pseudo-steady to chaotic transition	210.8 ms
a-ARC14	3 kA	Pseudo-steady to chaotic transition	48.6 ms
a-ARC15	3 kA	Cathode fireball	18.0 ms
a-ARC16	3 kA	Pseudo-steady to chaotic transition	73.0 ms
b-ARC02	3 kA	None observed/weak cathode fireball	-
b-ARC04	3 kA	Cathode fireball	24.2 ms
b-ARC05	3 kA	Cathode fireball	22.2 ms
b-ARC06	3 kA	Pseudo-steady to chaotic transition	132.4 ms
b-ARC07	3 kA	Cathode fireball	49.0 ms
b-ARC08	1.5 kA	None observed	-
b-ARC09	1.5 kA	None observed	-
b-ARC10	1.5 kA	None observed	-
b-ARC11	3 kA	Cathode fireball	21.0 ms
b-ARC12	3 kA	Cathode fireball	22.2 ms
b-ARC13	3 kA	None observed	-

Transitions in arc behaviour are seen to be important from qualitative observations of arcs near to the point of extinction. As a result, further arc testing was performed during which transition events were measured electrically together with synchronised high-speed imaging data. Results from a typical test are shown in Figures 3 and 4.

The transition sequence that typically occurs immediately prior to arc extinction has a substantial impact on the electrical behaviour of the arc. The formation of a fireball at the cathode surface as shown in Figure 3(b) results in a very rapid and large spike in the arc voltage. This suggests that the fireball is in fact a *low-temperature* phenomenon which momentarily *raises* the electrical resistance of the arc as it forms - this may be due to the fireball being formed by surface ablation of graphite from the cathode, which would occur at temperatures well below that of the bulk plasma. With the dissipation of the fireball and establishment of a pseudo-steady arc jet as shown in Figure 3(c), the system voltage drops rapidly to a low level, indicating that this arc geometry results in a lower electrical resistance than the more complex, twisted structures common during normal arc operation. Conversely, as the arc transitions away from the pseudo-steady state back to highly mobile, chaotic behaviour as shown in Figure 3(d), the voltage rises rapidly as the electrical resistance of the system increases.

(a) Chaotic motion, -595.8 ms (b) Cathode fireball, -506.8 ms (c) Pseudo-steady state, -338.4 ms (d) Chaotic motion, -256.0 ms

Figure 3. Sequence of frames from arc transition test at 3kA, showing various behavioural phenomena associated with arc extinction

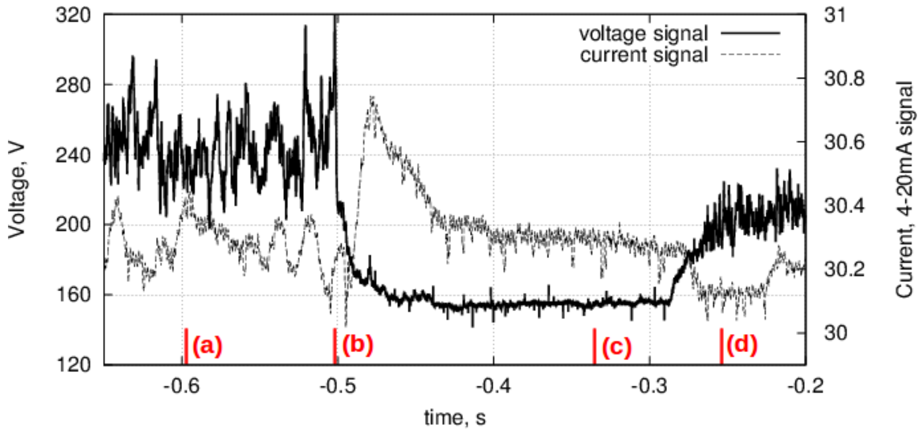


Figure 4. Measured voltage and current data for arc transition test (annotations refer to Fig. 3)

Using the interpretation of the cathode fireball phenomenon as a low-temperature gas/plasma cloud formation, a computational model of the arc system was constructed to study the evolution of the arc behaviour after such an event. The model solves the fully-coupled fluid flow, heat transfer, and electromagnetic fields in the arc region in time and three-dimensional space, and is described in detail elsewhere [Reynolds et al. (2010)]. The fireball was simulated by inserting a hemisphere of stagnant plasma centered on the cathode electrode at the halfway point of the simulation. The fireball temperature was set at 7000K. The arc length in this simulation is 50mm, and the current was fixed at 0.5kA. 2D side-on projections of the 3D temperature field in the cathode region of the model are shown in Figure 5, where the scale is from 2000K (black) to 15000K (white).

It can be seen by comparison with Figure 3 that although the time and size scales in the model are quite different to those in the arc extinction testwork, the arc behaviour resulting from a low-temperature cathode fireball in the model is qualitatively similar to that observed during transition events prior to arc extinction. The normal chaotic arc in Figure 5(a) is disrupted by the insertion of the fireball, which then disperses very rapidly. A strong, pseudo-steady arc jet forms through the fireball as shown in Figure 5(c), however this state soon breaks down with the onset of oscillations and the resumption of chaotic dynamics seen in Figure 5(d).

Figure 6 shows the arc voltage sequence generated by the model, and confirms the similarities with measured transition events as shown in Figure 4. The initial fireball

(a) *4.54 ms* (b) *5.00 ms* (c) *5.37 ms* (d) *6.51 ms*

Figure 5. Model results for arc evolution as a result of low-temperature cathode fireball

causes a peak in voltage, followed by a rapid drop to low voltages as the pseudo-steady state develops, and finally a return to higher voltages as chaotic motion resumes.

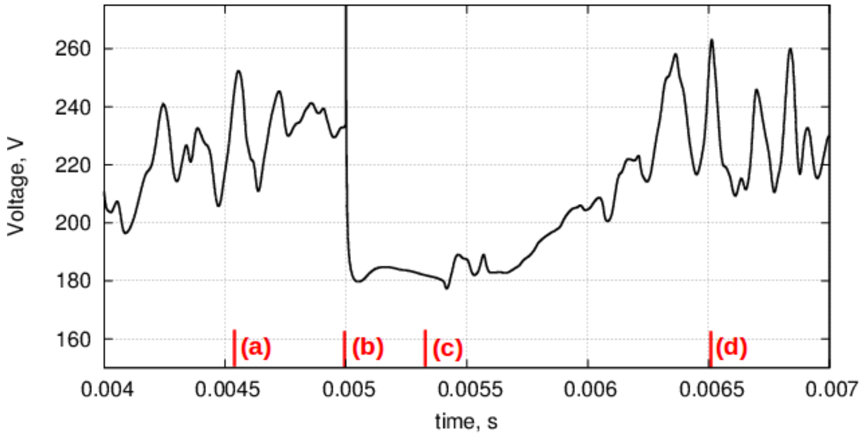


Figure 6. Measured voltage and current data for arc transition test (annotations refer to Fig. 5)

Although the current supplied to the arc is theoretically perfect DC (as used in the model), real-world limitations of rectification technology and the fact that the arc is only part of the complete electric circuit mean that some short-term fluctuation in current is likely. The arc is predominantly driven and heated by energy input by the current, and variations in current flow can be expected to increase the chances of an arc extinction event. This is particularly true of drops in current, during which the plasma gas in the arc can cool and become more electrically insulating.

In order to understand how the arc transition events identified earlier can affect the circuit behaviour, a very simple model of the power supply and arc load may be constructed as shown in Figure 7. Here, the power supply is modelled as a constant-voltage device, with the voltage value being controlled by a linear proportional controller based on the measured current and current setpoint (in reality the control action is more complex and may affect both current and voltage values simultaneously, for example changing the firing angle on a thyristor bank, and high performance model-based controllers are more typically used). The power supply contains an inductive load **L** by design, and the arc provides a time-dependent resistance **R** which is affected by changes in arc behaviour.

A typical response for such a circuit is shown in Figure 8. In this example **L** was taken as 300μH, the proportional control constant was set at 2.5 V/A.s, and the current setpoint was fixed at 3kA. It can be seen that step changes in arc resistance result in a temporary increase or decrease in current before the power supply reacts to bring the system back to the setpoint. It is interesting to compare this result with Figure 4, which shows qualitatively similar real-world behaviour occurring during arc transition events.

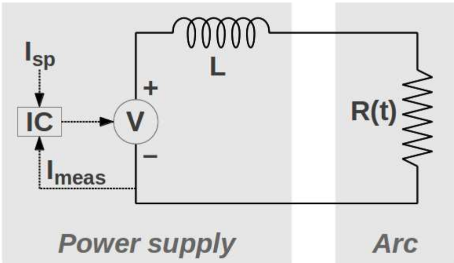


Figure 7. Simplified circuit diagram

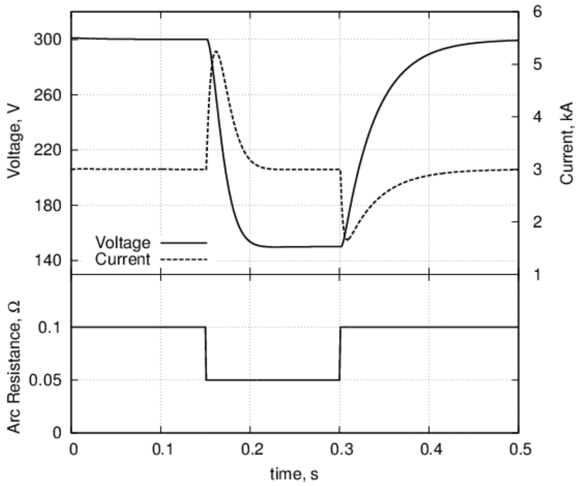


Figure 8. Circuit response to step change in **R**

This analysis suggests a possible reason for the correlation between arc extinction and either the cathode fireball phenomenon, or the transition from a pseudo-steady state to chaotic arc motion: both of these events cause a sudden *increase* in the resistance of the arc. As shown in Figure 8, such events may be expected to cause a momentary drop in the current supplied to the arc by the rectifier, and hence increase the probability of extinguishing the arc at that point.

4. Conclusions

Theoretical and experimental study of the phenomena involved in DC plasma arc extinction events has produced a number of novel results. The behaviour of the arc in the moments before extinction was characterised by a repeatable sequence of events consisting of the formation of a fireball of gas and plasma at the cathode electrode surface, the establishment of a pseudo-steady state with a strong directional arc jet present, and finally the breakdown of the pseudo-steady state into chaotic dynamics. Computational models of the arc demonstrated that the behaviour seen can be qualitatively accounted for by assuming that the cathode fireball is a low-temperature, high-resistance phenomenon. A simple circuit model of the arc and power supply system has shown that sudden increases in the resistance of the arc (associated both with the cathode fireball and the breakdown of the pseudo-steady state) could result in a decrease in electric current, potentially precipitating an extinction event.

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